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Energy Analysis of Waste Heat Recovery Boiler used in Cement Industry

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Abstract— Cement production is an energy intensive process. Known energy sources exhausted from cement industries. Effective utilization of these sources is required in order to improve the efficiency of the plant. In this dissertation work Preheater boiler and Air quench cooling (AQC) boiler is designed in order to recover the waste heat from the exhaust gases. The detail boiler design is carried out considering the various limitations to produce the superheated steam at higher temperature from the waste heat recovery boilers. Thermal design of both the boilers is carried out according to Babcock & Wilcox design guidelines. The steam pressure is limited around 16 to 17 bar so that cogeneration cycle efficiency is higher. Pinch point temperature imposed the certain limitations in the design. Higher pinch point temperature may reduce the external irreversibility but on the other side it would increase the required heat transfer area. Pinch point temperature is limited to 15 °C so that effective heat transfer takes place in evaporators and superheaters. The exhaust gas temperature is limited above the acid dew point temperature to avoid the corrosion problems over the tubes.

Keywords: Waste heat recovery, PH Boiler, AQC Boiler, Energy Analysis, Cement Plant

I. INTRODUCTION

India is the world's second largest cement producer after China, accounting for about 8% of the world's production. Annual per-capita consumption of cement in India is around 150 kg, which is much lower than the global average of 270 kg. Cement is one of the core industries, which plays a vital role in the growth of the nation. Limestone and coal being the basic materials for cement manufacturing, India has the requisite quantity of cement grade limestone deposits, backed by adequate reserves of coal. India also has the requisite technical expertise to produce the best quality of cement with the most energy efficient processes. Many Indian companies have attained high levels of energy efficiency in their plants, which are comparable to international benchmarks.

For a variety of applications, various types and grades of cement are used. The most common types of cement are Ordinary Portland Cement (OPC), Portland Pozzolana Cement (PPC) and Portland Slag Cement (PSC). Indian cement industry produces various types of cements such as OPC, PPC, Portland Blast Furnace Slag Cement or PSC, oil-well cement, rapid hardening - Portland cement, sulphate - resisting portland cement & white cement. In the year 2013-14, OPC production accounted for about 25% of the total production, while the blended cements, PPC & PSC accounted for 66% & 8% of the production respectively.

A. *The Cooling Process*

A substance is normally cooled by placing it with to some colder material. To make the substance super cold, however, heat must be removed and the substance must be insulated (encased). An important process of cryogenic super cooling includes liquefying gases and using these gases to cool other substances. One technique is to convert to liquid form a gas that can be liquefied by pressure only. Then a gas requiring a lower temperature to become a liquid is placed in a vessel and immersed (dipped) in the first. The gas that is already liquefied cools the second and converts it to a liquid. After several repetitions of this process, the targeted gas is liquefied. A Dewar flask is basically used to store such very low temperature liquefied gases.

II. KILN FLUE GAS CHARACTERISTICS

A. *Compositions of Flue Gas*

The flue gas coming out of suspension preheater is mainly mixture of following gases as shown in Table 5. The flue gas contains considerable amount of dust (typically 50 to 120 g/Nm³). The dust carried along with flue gas consists of ground raw material. It is sticky in nature and powdery form like talc. If not removed, the deposition of dust goes increasing, and then it is very difficult to remove it. Special mechanism need to be considered for dust removal in boiler.

Gas Constituents	Flue Composition, % v/v
Carbon Dioxide, CO_2	29.80
Moisture, H_2O	9.80
Nitrogen, N_2	56.80
Oxygen, O_2	3.40
Carbon Monoxide, CO	0.20
Sulfur Dioxide, SO_2	0.00
Flue gas pressure, mmWC	
Flue gas temperature, °C	
Dust load, g/Nm³	50-120

Table 4: Typical flue gas composition from Suspension Preheater

The hot gases from air quench cooler is nothing but air circulated by large industrial fans. This hot air also brings dust along with it. This dust consists of clinkers which are hard and abrasive in nature. The typical AQC boiler flue gas consists of following composition

Gas Constituents	Flue Composition, % v/v
Carbon Dioxide, CO_2	0.10
Moisture, H_2O	0.10
Nitrogen, N_2	79.00
Oxygen, O_2	20.80
Carbon Monoxide, CO	0.00
Sulfur Dioxide, SO_2	0.00
Flue gas pressure, mmWC	200-300
Flue gas temperature, °C	200-240

Dust load, g/Nm^3	30-50

Table 5: Typical flue gas composition from Air Quench Cooler

III. CEMENT WASTE HEAT RECOVERY POWER PLANT

Approximately 26% of the heat input to the system is lost by dust, clinker discharge, radiation and convection from the kiln and pre-heaters. In India, the specific energy consumption is about 3.06 GJ/t while in some countries of world it is lower than the 2.95 GJ/t. Where, on an average, 25% electrical energy and 75% thermal energy is used as an input energy.

This suggests that research is required to recover the waste heat from cement industry to improve its efficiency. There is more potential in cement industries for electric power generation using waste heat recovery compared to the other industries. Utlu et al. [1] suggested waste heat recovery to a cement plant to increase the energy efficiency of plant.

Fig. 7: Schematic diagram of cement plant with waste heat recovery (WHR)

Generally the temperature of flue gases and hot air leaves from the gas preheater stages and clinker cooler is around 200 to 500°C. This high temperature gases can be utilized to produce the high pressure superheated steam. Preheater boiler and Air quench cooling boiler are used to recover this waste heat. This superheated steam is further utilized for producing power. Figure 1 shows the schematic diagram of cement plant along with waste heat recovery system. Power generation per ton clinker of the waste heat is generally around 30.75 kWh/t [2].

A. *Description of Plant*

Considering the potential heat values of the waste flue gases from cement plant clinkerization process, it is proposed to install the "waste heat recovery based power plant". The heat values of pre-heater exhaust gases and clinker cooler vent would be utilized in the waste heat recovery boilers to generate the steam. The generated superheated steam would be introduced to the steam driven turbine generator set. The generated power is being used by cement plant operations.

The AQC boiler (Cooler vent waste heat recovery boiler) will be installed in the hot air circuit from the mid tapping taken from clinker cooler, which may carry highly erosive & abrasive clinker grains. De-dusting chamber will be provided in the cooler vent air, before entering the boiler to overcome the boiler abrasion.

PH boilers (Pre-heater exhaust gas waste heat recovery boilers) will be connected to the cement plant pre-heater exit and will produce the superheated steam. The exhaust steam of the turbine will be condensed in air cooled Condenser and it will be pumped to the de-aerator through condensate pre heater.

H boiler evaporator section is of horizontal, inline tubes and cross-flow arrangement with headers considering high dust content in the flue gas. This design feature to be considered must take into account minimum accumulation of dust on heating surface.

The AQC boiler evaporator section is horizontal inline tube arrangement with headers. The inclination is for facilitating natural circulation of steam water mixture. It shall be connected to the steam drum through adequately sized down comers and risers, to ensure adequate circulation under all operating conditions.

B. *Basis of Thermal Design*

The following table shows Flue gas parameters, steam / water parameters required for boiler design.

Name of the installation	Reliance Cement Company Private Limited	
Location	Bharauli, Maihar, Madhya Pradesh, India	
Ambient temperature (°C)	Max. 48 , Min. 7.0	
Wind velocity (max) (km/hr)	170	
Flue gas data	PH-1 Boiler	AQC boiler
Type of Boiler	Natural Circulation Water Tube Boiler	
Orientation of Boiler	Vertical	
Flue Gas Flow rate, Nm^3/hr	325000	200000
Gas temperature at boiler inlet, °C	287	427
Gas temperature at boiler outlet, °C	180±5	100±5
Flue gas composition (%v/v)		
CO_2	29.8	0.1
H_2O	9.8	0.1
N_2	56.8	79
O_2	3.4	20.8
CO	0.2	0
SO_2	0	0
Flue gas dust loading, gm/Nm^3(Max) at boiler inlet	75	50
Radiation Loss,%	2.0	
Steam Side Data	PH-1 Boiler	AQC Boiler
Gross steam generation required, kg/hr	16100	48600
HP steam temperature @ superheater outlet, °C	244±5	412±5
Feed water at LP PH ECO, °C	125	NA
Water Temperature	33 ^{0}C	
Condenser type	Air cooled condenser	
Condensing pressure	0.22 kg/cm^2 @ 45 ^{0}C	

Table 6: Boiler Design Datasheet
(Courtesy:-Thermax Ltd., Pune, India)

C. *Suspension Preheater Boiler*

The preheater boilers used in cement industries are of mainly two types.

- Horizontal preheater boiler
- Vertical preheater boiler

The hot gases coming out from the gas suspension preheater are admitted to the preheater boiler for recovering the heat. Generally the temperature of this gases lie between 240 to 390°C. The advantage of using gas suspension preheater is that one can utilize the low grade coal for preheating the raw-mix along with the hot gases coming from rotary kiln. The heat content of these gases depend upon the composition of the gases and the temperature at which these gases coming out from the suspension preheater. As the composition of gas change the properties of the gases change. The difference between two boilers is the arrangement of the tubes inside the boiler. Generally the vertical preheater boiler is used where the space availability is less.

Figure 8 shows the process flow diagram for vertical PH boiler. The boiler consists of HP and LP steam sections. High section consists of HP superheater, HP evaporator; while LP section consists of LP superheater, LP evaporator and LP economiser. LP steam is supplied to LP header for process purpose. The more details are shown in the following process flow diagram.

D. Boiler Design Requirement for Suspension Preheater Boiler

Owing to sticky and powdery nature of dust, the tubes of PH boiler are bare tube construction. Due to nature of dust it is very difficult to remove this dust easily from heat transfer surfaces. Hence, special mechanical hammering system is provided to dislodge the dust from heat transfer surfaces. The velocities in inside the boiler are kept such a way that no abrasion shall be foreseen.

- Bare tube construction
- Gas velocity below 12m/s
- Hammering system for dust removal.
- Multiple pressure sections as per clients requirement.

E. Air Quench Cooler Boiler

Figure 9 shows the process flow diagram for vertical gas path AQC boiler. It consists of superheater, evaporator, economiser, condensate preheater etc.

F. Boiler Design Requirements for AQC Boiler

The boiler is vertical single pass with bottom hot flue gas entry. The gas carries about 40-50 gm/Nm³ of dust which mainly clinker fines. The nature of dust is it is abrasive and non-sticky. Hence, spiral fins are provided in order enhance the heat transfer.

IV. OUTCOME OF CASE STUDY

A. Power Savings through Waste Heat Recovery Boilers & Cycle Efficiency

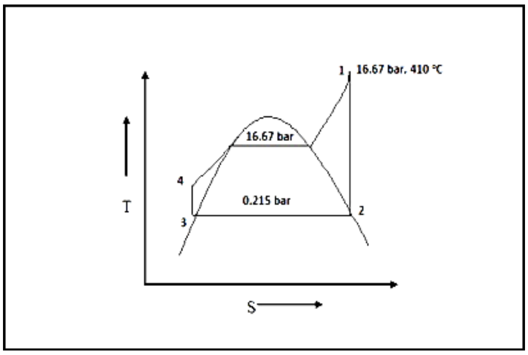

Fig. 13: T-s diagram for cogeneration cycle

Let,

h_1 is enthalpy of superheated steam entering turbine at 16.67 bar,410°C

h_2 is enthalpy of saturated steam leaving turbine at 0.215 bar, saturated

S_1 is entropy of superheated steam entering turbine at 16.67 bar, 410°C

S_2 is entropy of saturated steam leaving turbine at 0.215 bar, saturated

x_2 is dryness fraction of saturated steam leaving turbine

For given data, we can find out above parameters as follows:

$h_1 = 3275.33$ kJ/kg

$h_2 = 2403.6$ kJ/kg

Dryness fraction can be found out as follows:

$$S_1 = S_2 = S_{f2} + x_2 S_{fg2}$$

$7.25133 = 0.86225 + x\,(7.0079)$

$x_2 = 0.9116$

Work done by turbine (Wo) per kg of steam is given as:

$$W_o = (h_1 - h_2) = (3275.33 - 2403.6) = 871.73 \text{kJ/kg}$$

Total work done by turbine (WT) per kg of steam is given as:

$$W_T = m_s(h_1 - h_2)$$

where, m_s is the steam flow rate to turbine, kg/s

$W_T = 13.5\,(3275.33 - 2403.6) = 11768.35$ kW

Taking mechanical efficiency of turbine as 85% [11], the actual work useful work done is,

$$W_{actual} = 0.85\ W_T = 0.85 \text{ x } 11768.355 = 10003.101 \text{ kW}$$

Taking generator efficiency as 94% [11], the net power output (Pout) is given as,

$$P_{out} = 0.94\ W_{actual} = 0.94 \text{ x } 10003.101$$
$$= 9402.915 \text{ kW [11]}$$

Total heat input to the turbine (Qin) per kg of steam is given as:

$Q_{in} = (h_1 - h_4) = 3275.33 - 259.67 = 3015.652$ kJ/kg

Overall efficiency of the power plant is given as:

$$\text{Overall efficiency}(\eta_{system}) = \frac{\text{Work output}(W_o)}{\text{Heat input}(Q_{in})} = \frac{(h_1-h_2)}{(h_1-h_4)}$$

$$\eta_{system} = \frac{3275.33 - 2403.6}{3275.33 - 259.67} = 0.2890 \text{ i.e. } 28.90\%$$

$\eta_{system} = 28.90\%$

Overall energy saved per year = (Power generated) x (Hours of usage per year)

Energy saved (E_{saved})

$=$ Powergenerated (P_{out}) x hours of usage per year

$$\text{Energy saved }(E_{saved}) = (9402.915) \text{x} \left(8000 \frac{\text{hr}}{\text{yr}}\right) [8]$$

$E_{saved} = 75.223 \text{ x } 10^6 \text{kWh/year}$

6.4.2 Cost Savings Based on Case Study

The average unit price of electricity can be taken as Rs. 6.6 per unit (kWh), and therefore, the anticipated cost savings would be…

$$\text{Cost saving} = \text{Rs. } 75.223 \text{ x } 10^6 \text{x } 6.6$$
$$= \text{Rs. } 48.89 \text{ x } 10^7 \text{ per year}$$

Thus, it is concluded that Rs. 48.89 Cr can be saved per year.

V. RESULT & DISCUSSION

The cement industry is consuming large amount of thermal energy. Almost 75 % of total energy input required is thermal energy and the rest 25% is electrical energy. There are mainly two waste streams are observed while doing case study of J.K. Laxmi Cement Plant. The major source of heat losses are from exhaust gases from preheater and hot air from the clinker cooler. The suspension preheater boiler (PH) for exhaust gases and Air Quench cooling (AQC) boiler are designed in order to recover the waste heat. The waste heat recovery boilers are designed for Reliance cement industry, Maihar Unit-2, Madhya Pradesh. The energy savings of 75.22 × 106 kWh/year and cost savings of Rs. 49.64 Cr will be achieved through this cogeneration plant. However cost of installation and cost of maintenance are not considered.

However the implementations of waste heat recovery plant in existing J.k.Laxmi cement plant having the cost savings of Rs. 44 Cr. In order to improve the efficiency of cement plant, waste heat recovery system is suitable option.

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